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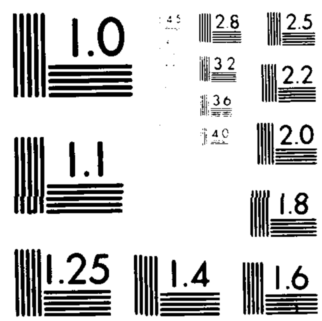

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PRELIMINARY ANALYSIS OF MOTION SICKNESS INCIDENCE DATA

by

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and
Dennis E. Smith

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I. INTRODUCTION

Over the past several years the Office of Naval Research (ONR) has supported research regarding the effects of various motion parameters on motion sickness and human performance response. (See [2, 7, 8, 12, 13], for example.) A major component of the research program has been the study of single and mixed frequency heave-induced motion sickness as experimentally imparted to subjects via the ONR motion generator. Experimentation has emphasized developing a means for predicting motion sickness incidence (MSI) in complex motions characteristic of ships at sea.

Based on the results of various single frequency experiments, an MSI predictive model [7] has been developed to predict the incidence rate of motion sickness on subjects exposed to motion defined by a single sinusoid. Using the occurrence (or nonoccurrence) of frank emesis as the diagnostic motion sickness criterion, this model predicts the probability of emesis as a function of wave frequency, rms acceleration, and an exposure time of not more than two hours duration. However, since ship motion tends to be broad-band, the single frequency model per se is not directly applicable in predicting the incidence of motion sickness in military personnel exposed to actual sea conditions.

Fundamental to the study of motion sickness is deciding at what level of symptomatology a subject can be said to be motion sick. Although emesis is an obvious and popular criterion for motion sickness, there are a number of reasons [11, 14] for avoiding frank emesis as an experimental endpoint for determining the presence of experimentally-induced motion sickness.

Accordingly, in a recent report [13] the need to identify measurable correlates of motion sickness was acknowledged and investigated. One aspect of that investigation was to determine the distributional characteristics of time to first emesis data.

Efforts [7, 8, 13] to characterize the distribution of time to first emesis have been typified by the fitting of Weibull and lognormal statistical models. However, on the whole, these efforts have been inconclusive in determining an adequate statistical model to describe emesis data. The apparent difficulties experienced by researchers in characterizing this phenomenon are in some measure attributable to the wide individual differences in motion sickness susceptibility, to the lack of observed data beyond two hours, and to an insufficient theoretical framework with which to organize and make sense of the many empirical facts and clinical observations.

Presently, there is little theoretical justification specific to the etiology of motion sickness for choosing any one particular probability distribution as the time to emesis model. The Weibull and lognormal models have been suggested primarily because of empirical and analytical considerations. Ideally, the final choice (or derivation) of a time to first emesis model should be based not only on the ability of a plausible distribution to explain the observed sample data, but also on the effective physiological, biochemical, and physical factors that individually or collectively may be responsible for motion sickness.

In short, to use a statistical model to characterize a phenomenon (such as time to first emesis) for which the trigger mechanism is not entirely known, is at most an approximation. Despite this fact, an appropriate statistical model often offers a degree of approximation that is adequate for

practical applications. In view of this situation, this technical report provides additional analysis of and comments on time to first emesis data.

II. TIME TO FIRST EMESIS

In order to explicitly examine the ability of the Weibull and the lognormal models to explain the observed emesis data, statistical tests of goodness of fit were performed. A goodness of fit test is a formal statistical test about the identity of a probability distribution that fits a set of data. Data from various single frequency studies (see [6] for a compilation) and data from the "Correlation Study" [2] were analyzed.

The latter study was designed to determine some of the effects of complex periodic waveforms on motion sickness. The complex waveforms examined were created by summing two harmonically related sinusoids, of which the fundamental frequency component served as a single-frequency control. Figure 1 summarizes the motion parameters defining the five experimental conditions studied in the "Correlation Study".

A. DATA AS CENSORED SAMPLES

Since the experimental sessions in all studies were limited to a two-hour duration or stopped due to emesis, data beyond two hours is not available. Initially, therefore, goodness of fit tests appropriate for censored samples were applied. Conditions in which the degree of censorship exceeded 70%, however, were omitted since the severity of censorship prohibited a definitive analysis.

A modified Cramér-von Mises type statistic [3, 9, 10] was used to test the hypothesis of a censored lognormal distribution as the time to first emesis model. The ordinary Cramér-von Mises statistic is given by

	Condition				
	I*	II	III	IV	V
Fundamental:					
Frequency (Hz)	.17	.17	.17	.17	.17
rms Acceleration (g)	.14	.14	.14	.14	.09
Harmonic:					
Frequency (Hz)	---	.33	.33	.50	.33
rms Acceleration (g)	---	.15	.13	.29	.24
Phase Angle (degrees)	---	0	+90	0	0
Total Acceleration:					
rms Acceleration (g)	.14	.21	.19	.32	.26

*Single-frequency control.

FIGURE 1: Recorded Motion Parameters of "Correlation Study" Waveforms.

$$n\int_{-\infty}^{\infty}[F_n(x) - F_0(x)]^2 dF_0(x)$$

where n denotes the sample size, $F_n(x)$ denotes the empirical distribution function, and $F_0(x)$ denotes some specified distribution function. The modified version of this statistic takes into account the censoring and the lack of a completely specified distribution function.

The test of fit for a censored Weibull distribution was based on the ratio of the sum of differences of adjacent order statistics divided by their expectations [5]. Because both testing procedures are fairly sophisticated and detailed, they are not described further. For more complete discussions of the testing procedures, the indicated references may be consulted.

Conditions were separately analyzed with the results summarized in Figure 2. Provided the sample data is regarded as a censored sample, the results of Figure 2 do not favor either the Weibull or the lognormal family of distributions as a potential generic time to emesis model, nor do any systematic tendencies appear to be present.

B. POOLING OF DATA

As an alternative to analyzing the conditions separately, one suggestion has been to pool or to sort the data into groups and then to analyze the times to first emesis. For instance, in [13] all conditions of vertical sinusoidal motion in which the cumulative MSI within two hours exceeded 30% were placed into a high incidence group and the remaining conditions (less than 30% cumulative MSI) were placed into a low incidence group.

The severity of censorship in the low incidence group (only 20 of a

Condition Description		Ratio of subjects who vomited within two hours to total number of subjects tested	Reject hypothesis of censored lognormal at .05 level of significance	Reject hypothesis of censored Weibull at .05 level of significance
Frequency (Hz)	Acceleration (rms)			
.167	.111	7/21	Yes	Yes
.167	.222	11/20	Yes	Yes
.250	.111	9/29	Yes	No
.250	.222	37/59	No	Yes
.333	.222	15/28	No	No
.333	.333	17/34	No	Yes
.500	.444	7/21	Yes	Yes
Correlation Study Condition				
I		16/32	Yes	Yes
II		16/32	No	No
III		20/31	No	Yes
IV		21/31	No	Yes
V		25/32	No	No

FIGURE 2: Results of Goodness of Fit Tests for Censored Samples.

possible 205 subjects vomited within two hours) precluded analysis. However, for the high incidence group (in which 49 of 100 subjects vomited within two hours) a goodness of fit analysis rejected (at the .05 level of significance) both the censored Weibull and the censored lognormal as time to first emesis models.

Care, however, must be exercised when interpreting the results of a "pooled" analysis, especially since time to first emesis is notably dependent on the frequency and amplitude of motion. Collapsing condition-dependent data by condition may yield a result that is no more than an artifact of the pooling. Therefore, until time to emesis in separate motion conditions is better understood, it is probably advisable not to pool data across conditions. One situation, however, in which pooling might be somewhat reasonable involves data from a study [7] to determine the effects of pitch or roll when added to a constant .25 Hz, .11 g rms sinusoidal vertical oscillation. Since the addition of pitch or roll was found to have no significant effect on heave-induced MSI, at least a statistical premise for pooling is established. The thirteen conditions with and without pitch or roll were subsequently pooled and a goodness of fit analysis was performed. Again, both the censored Weibull and censored lognormal were rejected (at the .05 level of significance) as time to first emesis models.

C. DATA AS COMPLETE SAMPLES

It would appear, therefore, that the observed data is inadequately explained by regarding the data as a censored Weibull or a censored lognormal model. In lieu of regarding the data as a censored sample, another approach has been to ignore the truncation and treat the uncensored portion of the

data as a complete sample. Accordingly, tests of fit appropriate for complete samples were applied to the uncensored times of the same twelve motion conditions examined in Figure 2.

In order to test the hypothesis of a lognormal distribution, the uncensored times were ordered, subjected to a logarithmic transformation, and plotted on normal probability paper. A probability plot correlation coefficient test was then performed [1]. In order to test the hypothesis of a Weibull distribution, a testing procedure similar to the goodness of fit test for a censored sample [5] was applied to the data. The results are summarized in Figure 3.

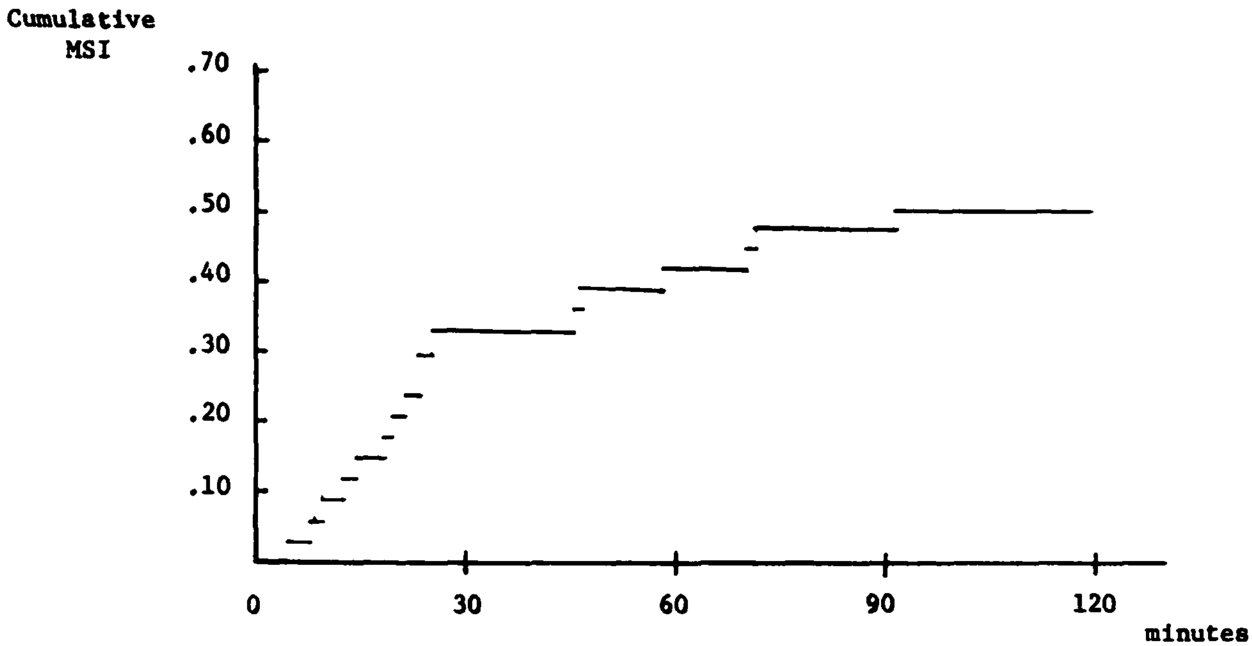
Whereas the lognormal model is rejected (at the .05 level of significance) in six of the twelve conditions examined, the Weibull model is rejected only once. Since at the .05 level of significance one incorrect rejection is to be expected in every twenty tests, the results serve to support the use of the Weibull model as a generic time to emesis distribution for the uncensored portions (i.e., emesis within two hours) of the observed data. An overall time to emesis model, however, must also take into consideration the censored portion of the sample data.

D. A STATISTICAL MIXTURE MODEL

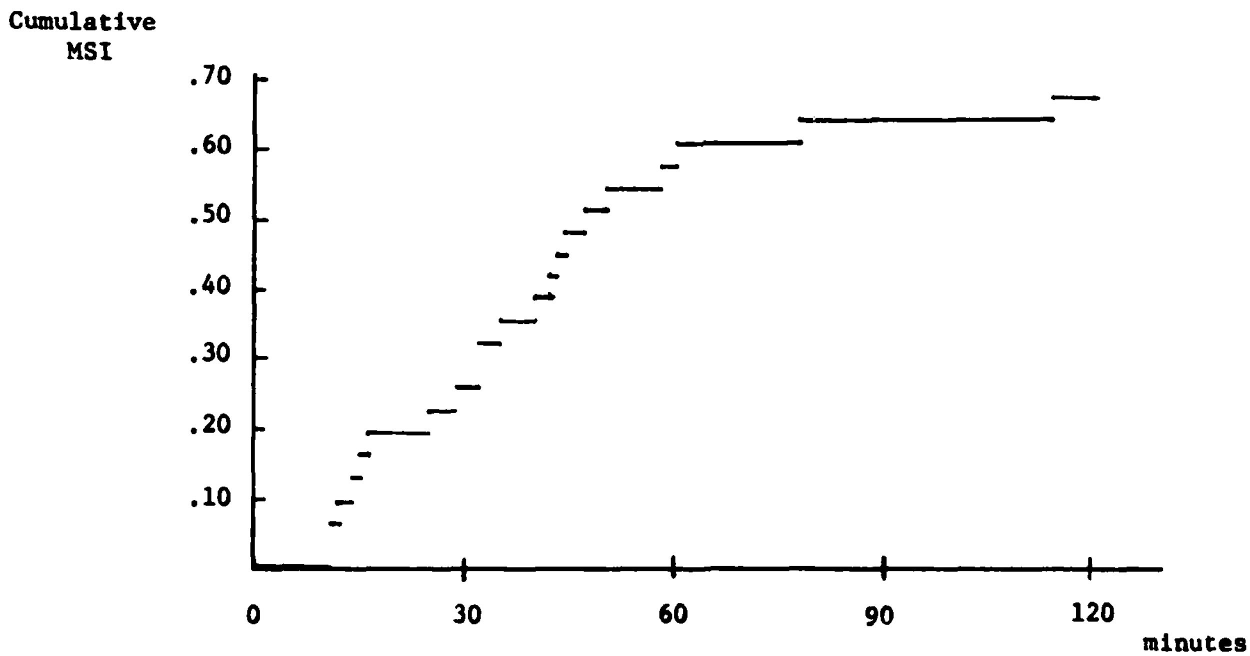
In light of the truncation that was ignored to analyze the uncensored portion of the sample data and the general leveling off of cumulative MSI beyond a 90 minute exposure in all the conditions examined (see Figure 4, for example), a possible mixture of distributions as an overall time to first emesis model is suggested. It is reasonable, therefore, to postulate a mixture of two population--a Weibull distribution to model earlier (sometime

Condition Description		Size of uncensored portion	Reject hypothesis of Weibull model for uncensored portion of sample at .05 level of significance	Reject hypothesis of lognormal model for uncensored portion of sample at .05 level of significance
Frequency (Hz)	Acceleration (rms)			
.167	.111	7	No	No
.167	.222	11	No	Yes
.250	.111	9	No	No
.250	.222	37	No	Yes
.333	.222	15	No	No
.333	.333	17	No	Yes
.500	.444	7	No	No
Correlation Study Condition				
I		16	Yes	Yes
II		16	No	No
III		20	No	Yes
IV		21	No	Yes
V		25	No	No

FIGURE 3: Results of Goodness of Fit on Uncensored Portions of Samples.



Condition: .333 Hz, .333g rms



Condition: IV of "Correlation Study"

FIGURE 4: Two empirical cumulative MSI functions. These graphs are typical of the leveling in MSI exhibited by all twelve motion conditions examined.

within 120 minutes) time to emesis and some other indeterminate (because of the truncation) distribution to model later (sometime beyond 90 minutes) time to emesis. Reference [4] can be consulted for a joint discussion of mixtures and the Weibull distribution as a time to failure model.

In more formal terms, if $F(t)$ denotes cumulative MSI as a function of time, t, and if $F_1(t)$ and $F_2(t)$ denote the two subpopulation cumulative MSI functions, then it is conjectured that $F(t) = pF_1(t) + (1 - p)F_2(t)$, for $0 \leq p \leq 1$ and $t \geq 0$. The mix parameter p represents the proportion of the total population that is comprised by the subpopulation $F_1(t)$.

Because of the general leveling and stabilizing of cumulative MSI beyond 90 minutes, it is further surmisable that the degree of subpopulation overlap is relatively small. Equivalently, the degree of subpopulation separation is relatively large. See Figure 5 for a hypothetical illustration. Consequently for $0 \leq t \leq 120$, $F(t) \simeq pF_1(t)$ where $F_1(t)$ arbitrarily denotes the Weibull subpopulation component. Assessing the behavior of $F(t)$ for $t > 120$ will, of course, require experimentation lasting longer than two hours.

The mix parameter p, the parameters of the mixture subpopulations, and the degree of subpopulation overlap will undoubtedly depend on the motion parameters that define the particular motion stimulus. However, the exact nature of these relationships is presently unknown. Although the conjectured mixed statistical model is appealing, the general validity of this model and its postulated characteristics will require further independent testing, especially on motion conditions differing from those analyzed within this report.

It should be noted that the time to emesis model proposed herein does

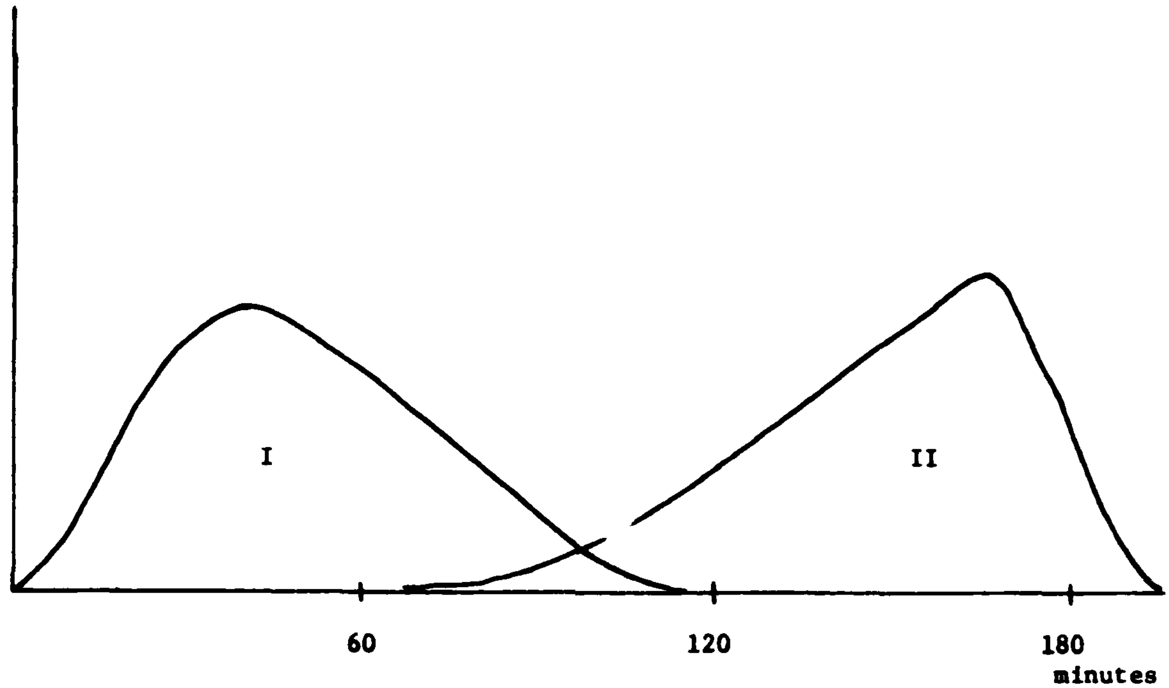


FIGURE 5: A hypothetical configuration of two subpopulation probability density functions. (In order to form the overall time to first emesis mixed density, I and II would be proportionately combined according to the mixture parameter, p. Note the degree of overlap. Furthermore the shape of density II is purely hypothetical since no data beyond two hours is available.)

not concur with the conclusions expressed in [13]. In that report, the uncensored portions of the five experimental conditions examined in the "Correlation Study" were ordered, assigned median ranks and plotted on Weibull probability paper. The plotted data seemed to exhibit two "excellent" straight line fits; hence the existence of two distinct populations within the uncensored portion of the sample data was surmised.

The goodness of fit tests summarized in Figure 3, however, do not substantiate the existence of two Weibull models within the uncensored portion of the sample data. These formal tests indicate that a single Weibull model provides an adequate fit. Thus, a single straight line should actually provide a sufficient fit to the probability plots (except perhaps for condition I). This is seen more clearly with the addition of confidence bands to the probability plots. The confidence bands may be determined by applying the formulas given in [5].

As an illustration, the data from condition III of the "Correlation Study" was plotted on Weibull probability paper as shown in Figure 6. The plotted data together with the two straight line fits of reference [13] are displayed in Figure 7. The data is again plotted in Figure 8, but this time 95% confidence bands are included.

Two reasonable straight lines (labeled A and B) that lie within the confidence bands are exhibited in Figure 8 to illustrate the adequacy of a single line fit. As can be seen from this figure, the confidence bands are relatively wide for the shorter times and relatively narrow for the longer times. Thus, an apparent departure from a straight line fit may be reflecting only statistical variation, particularly if that departure corresponds to a short time.

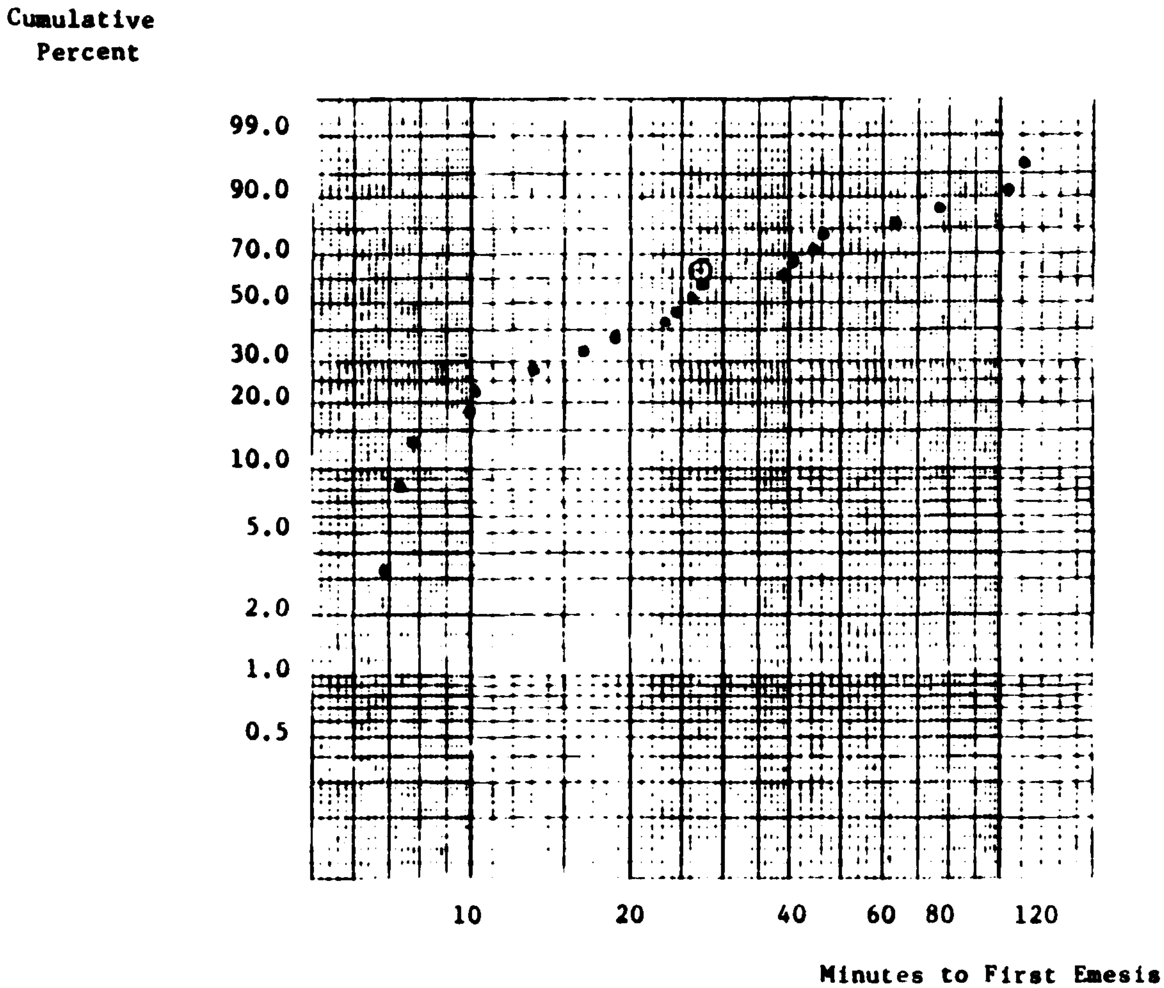


FIGURE 6: A Weibull Plot of Condition III for the "Correlation Study."

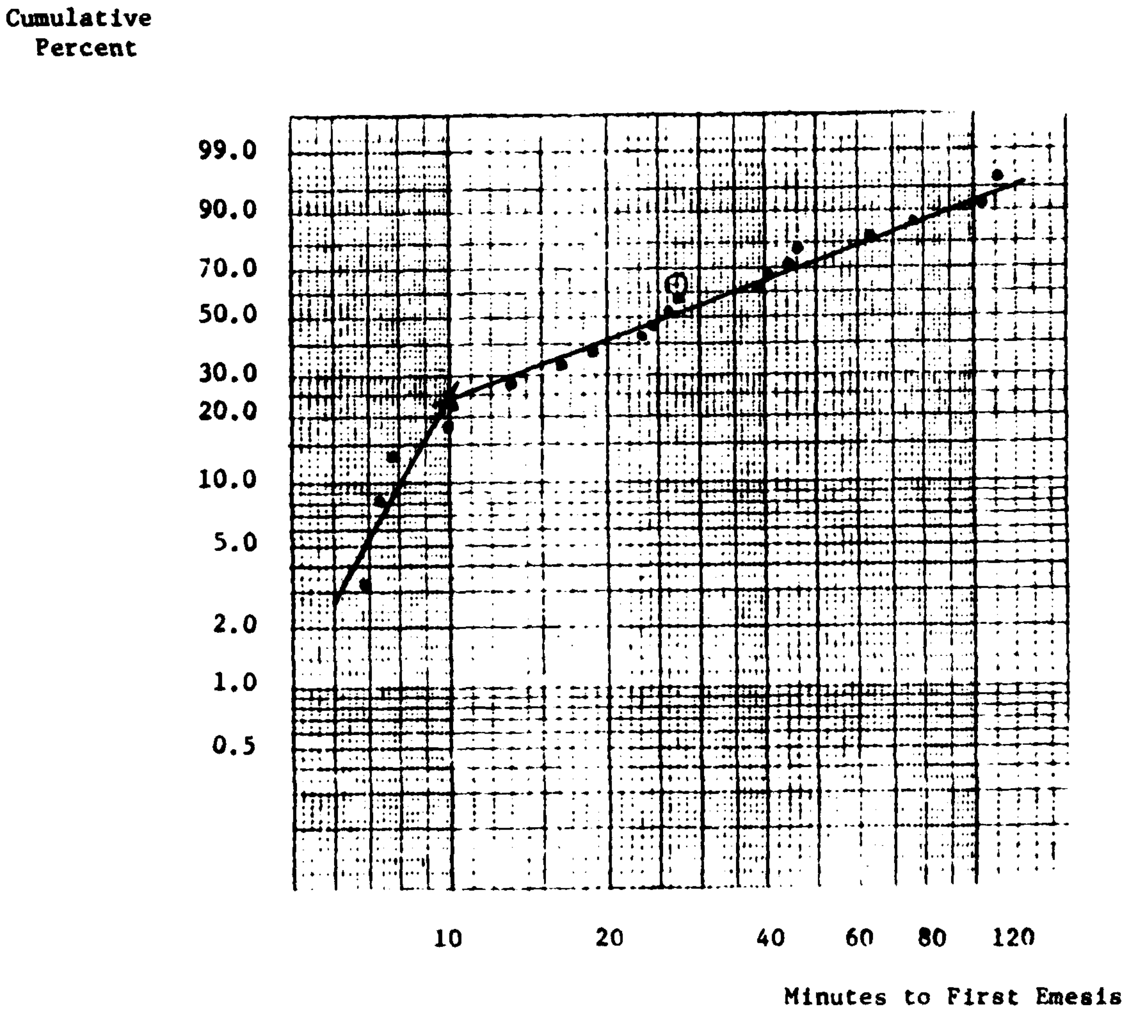


FIGURE 7: Two Apparent Straight Line Fits to the Data.

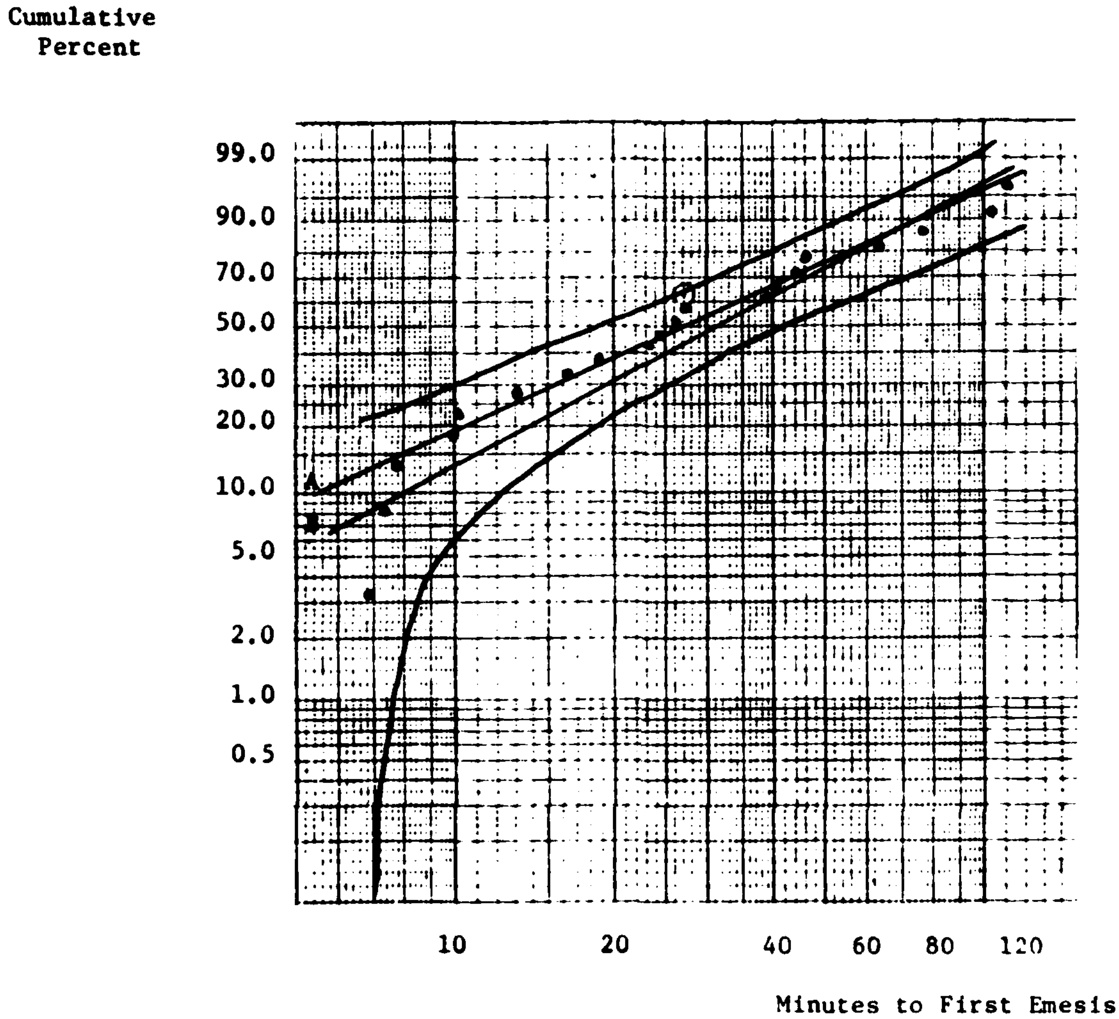


FIGURE 8: Two Reasonable Single Straight Line
Fits within the Confidence Bands.

III. DISCUSSION

This report has analyzed motion sickness data that has been obtained from experiments involving the ONR motion generator. Based on the analysis, a mixture of two statistical populations has been postulated as an overall model of time to first emesis. Empirical evidence indicates that the subpopulation corresponding to early emesis is Weibull. However, data from longer experiments with differing motion conditions is required in order to determine the complete structure and the general applicability of such a mixture model.

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This report analyzes motion sickness data obtained from experiments involving the Office of Naval Research motion generator. Based on the analysis, a mixture of two statistical populations has been postulated as an overall model of time to first emesis.

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